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TVA's 1-MW Pilot Plant: Final Report on High-Velocity Scrubbing and Vertical Duct Mist Elimination

Tennessee Valley Authority, Chattanooga Power Research Staff

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TVA'S 1-MW PILOT PLANT: FINAL REPORT ON HIGH VELOCITY SCRUBBING AND VERTICAL DUCT MIST ELIMINATION

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16. ABSTRACT The report describes the systematic test program that led to the development of washing techniques that maintain continuous mist eliminator performance for lime/limestone closed-loop scrubbing systems. TVA recently demonstrated the techniques at its 1-MW pilot plant at the Colbert Power Plant. The report also describes high-velocity scrubbing tests performed in conjunction with the mist eliminator tests. Continuous operation of the chevron mist eliminator, positioned horizontally in a vertical duct, in the limestone system was maintained (after extensive testing at 12.6 ft/sec) by washing the bottom of the mist eliminator intermittently with all the available clarified liquor, immediately followed by an allocated amount of makeup water. The top of the mist eliminator was washed intermittently with the remaining allocation of allowable makeup water. At a gas velocity of 16 ft/sec, the scrubber operated more efficiently and mist eliminator performance was improved. Continuous mist eliminator performance in the lime system was maintained at 12.5 and 16 ft/sec by washing the bottom of the mist eliminator intermittently with an allocated amount of allowable makeup water. The remainder of the allocated makeup water was used to intermittently wash the top of the mist eliminator.

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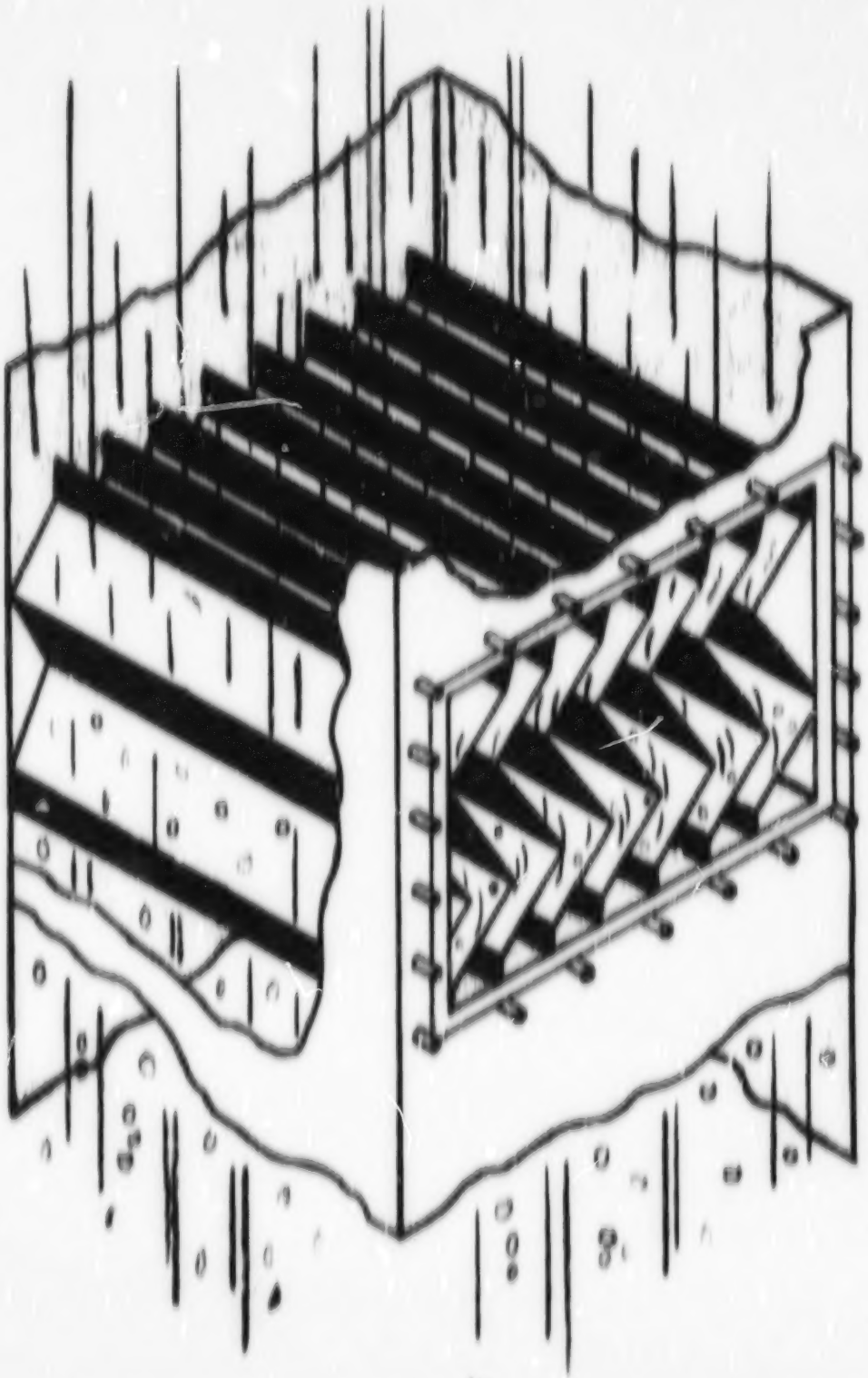
ABSTRACT

TVA has recently demonstrated washing techniques that maintain continuous mist eliminator performance for lime/limestone closed-loop scrubbing systems at its 1-MW pilot plant at the Colbert Power Plant. The systematic test program which developed these washing techniques is reviewed for both the limestone and lime systems. High velocity scrubbing tests were also performed in conjunction with the mist eliminator tests. Continuous operation of the Chevron-type mist eliminator, positioned horizontally in a vertical duct, in the limestone system was maintained (after extensive testing at 12.6 ft/sec) by washing the bottom of the mist eliminator intermittently with all the available clarified liquor immediately followed by an allocated amount of makeup water. The top of the mist eliminator was washed intermittently with the remaining allocation of allowable makeup water. At a gas velocity of 16 ft/sec, the scrubber operated more efficiently and mist eliminator performance was improved. Continuous mist eliminator performance in the lime system was maintained at 12.6 and 16 ft/sec by washing the bottom of the mist eliminator intermittently with an allocated amount of allowable makeup water. The remainder of the allocated makeup water was used to intermittently wash the top of the mist eliminator.



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1. INTRODUCTION

TVA has operated the 1-MW wet lime/limestone pilot plant at the Colbert Steam Plant since February 1971. Until recently, the pilot plant was used primarily for testing limestone scrubbing with major attention directed toward the full-scale 550-MW Widows Creek limestone scrubbing system.

Results from this testing suggested utilizing a vertical mist eliminator in a horizontal duct. This type of mist elimination design permits the use of a wash system for the mist eliminator separately from that of the scrubber. More recently, the pilot plant tests were designed to evaluate similar methods for washing this type of mist eliminator without exceeding the water balance of the closed-loop limestone wet scrubbing process. The quantity of fresh water required for effective washing of the mist eliminator on a once-through basis was four to five times the amount required for makeup to the closed-loop slurry system. One such method of maintaining continuous operation of the mist eliminator in the horizontal duct while operating in a closed-loop slurry system is the use of sodium carbonate in the recyclable mist eliminator wash system. This additive increases the solubility of sulfates thus reducing the tendency for scale formation. The additive method may not be applicable for washing the mist eliminator in the vertical duct because of the difficulty in separating the wash liquor from the scrubber liquor. Such separation is necessary to avoid loss of sodium carbonate which would be prohibitively expensive.

The current project was primarily aimed at finding a washing technique for maintaining continuous reliable mist eliminator performance in a closed loop lime/limestone scrubbing system where the mist eliminator was positioned vertically in a horizontal duct. At a gas velocity of 9

ft/sec, the problem of plugging has generally been resolved. At gas velocities greater than 9 ft/sec, mist eliminator plugging was still a problem. Scrubbing techniques had been established for a gas velocity of 10.6 ft/sec, and this velocity was the preferred operating velocity. At 16 ft/sec, testing of an advanced high velocity scrubber was done in conjunction with the mist eliminator study.

F. SUMMARY AND CONCLUSIONS

Pilot-plant tests have demonstrated washing methods that maintain continuous mist eliminator performance. Continuous performance of a horizontally mounted mist eliminator operating in the limestone mode is difficult because the wash water required for proper washing cannot be separated from the slurry system. Closed-loop operation precludes using copious amounts of fresh water to maintain reliable mist eliminator performance since the allowable makeup water rate is approximately 0.7 gpm or 0.8 gpm/ft^2 of duct area. The vendors recommended a wash rate of 5 gpm/ft^2. An intermittent wash using additional sources of wash liquor had to be used.

Washing the mist eliminator intermittently in the limestone mode with fresh makeup water was not successful. This may partly be attributed to operating the limestone mode at a stoichiometry of 1.5. Operation of this stoichiometry increases the plugging potential with soft mud-like solids due to excess limestone in the scrubbing slurry being entrained into the mist eliminator. The accumulation was at such a rate that another liquid source was needed to wash the mist eliminator. The clarified liquor to the scrubber system was accumulated and used to wash the mist eliminator along with the allowable makeup water. Intermittent washing with clarified liquor immediately followed by the makeup water allocation was successful in removing the soft mud-like solids and the calcium-sulfur salts from the bottom of the mist eliminator--thus preventing the formation of scale. The top was washed intermittently with the remaining allocation of allowable makeup water. Continuous mist eliminator performance was maintained with this method.

Washing the mist eliminator intermittently in the lime mode with fresh makeup water was successful. The lime system operated at a stoichio-

metry of 1.0 which alleviated having excess alkali material present in the scrubbing slurry being entrained into the mist eliminator. Continuous mist eliminator performance in the lime mode was maintained by washing the bottom of the mist eliminator intermittently with an allocated amount of allowable makeup water. The remainder of the allocated makeup water was used to wash the top of the mist eliminator intermittently.

The pilot plant was modified for the advanced high velocity scrubbing tests by inserting additional slurry inlets within the beds of spheres. SO_2 removals in the lime mode were higher at the high gas velocity (16 ft/sec) than those observed in the previous tests at 12.6 ft/sec. This high removal is believed to result from improved mixing and a higher dissolution of the lime. The mist eliminator was washed with fresh water only using the washing technique of the successful lime run. This washing technique kept the mist eliminator clean for the 500-hour long-term run at both 12.6 ft/sec and 16 ft/sec.

In the limestone mode, SO_2 removal was also higher at the higher gas velocity. The effect of the sprays in the beds was shown to improve SO_2 removal. However, the mist eliminator, washed intermittently with only fresh water, showed signs of solids buildup. The need of more wash water is evident.

The conclusions drawn from this study are as follows:

- Proper application of the available wash water and the wash frequency is the key contributor in maintaining continuous mist eliminator performance.
- Limestone scrubbing requires additional washing (clarified liquor) than the fresh makeup water available.
- A higher limestone stoichiometry (1.5 vs. 1.25) requires additional mist eliminator attention.
- Lime scrubbing requires only fresh makeup water for mist eliminator washing.

- The results do not say that all mist eliminator problems can be solved, but the progress in that direction is certainly encouraging.
- High velocity scrubbing appears to improve scrubber operation. Additional testing is needed to investigate velocities higher than those attainable at Colbert.

3. TEST RESULTS

A flow diagram of the TCA limestone scrubbing system for the mist eliminator tests is shown in Figure 1. The pilot plant operated on a closed loop basis such that the only liquor purged from the system was that contained in the discarded spent solids (filter cake). This quantity of liquor amounted to about 140 pounds per hour when the filter cake contained 60 to 65 percent solids. Fredonia limestone (75% - 200 mesh) was fed to the system at a rate sufficient to maintain a $Ca:SO_2$ mole ratio of 1.5 based on the concentration of SO_2 in the inlet flue gas. Scrubbing slurry containing an average of 15 percent suspended solids and 1.25 percent dissolved solids was recirculated to the venturi and absorber at a liquid-to-gas ratio (L/G) of 10 and 50 gallons per 1000 cubic feet, respectively. The scrubber contained two stages (each 12 in deep) of 10-gram thermoplastic rubber (TPR) spheres manufactured by Holdcraft. The absorber operated at a

Figure 1. TCA limestone scrubbing flow diagram.

superficial gas velocity of 10.6 to 13.8 ft/sec. The concentration of SO_2 in the inlet gas varied from 1600 to 2700. The SO_2 removal for the limestone tests averaged 70 percent. This low SO_2 removal is attributed to the absorber inlet spray header being lowered (approximately 15 ft) to just beneath the third grid so that the mist eliminator could be installed between the third and fifth grids. The particulate loading in the inlet and outlet averaged 4.5 and 0.09 grains per standard ($60^{\circ}F$) cubic foot, respectively. The pressure drop across the venturi and TCA-type absorber (containing 3 grids and 2 stages of the TPR spheres) averaged 9 and 7 inches of water, respectively.

The initial run was designed to observe drainage and mist entrainment from the mist eliminator washes at superficial gas velocities of 5, 7.5, 10, 12.6, and 16 ft/sec using only air and water. Proper drainage of the mist eliminator occurred at 12.6 ft/sec--the planned operating velocity. The approximate loadings of entrained water entering and leaving the mist eliminator were determined by exposure of a specially treated filter paper. The filter paper, attached to a holder, was moved across the duct. To prepare the test paper, Whatman No. 1 filter paper was saturated with a 1 percent solution of potassium ferricyanide, thoroughly dried and dusted with finely divided ferrous ammonium sulfate. The dry, treated paper was pale yellow. A sharply defined, dark blue stain appeared when the paper was wetted by a water droplet. This gave an indication of water entrainment quantity. The approximate loading was measured by weighing the paper before and after exposure. The approximate loading of entrained water entering and leaving the mist eliminator with the wash sprays off was 5.3 and 0.32 grains per standard cubic foot, respectively.

Run ME-10 began on July 29, 1975, using flue gas and limestone slurry with an initial pressure drop across the mist eliminator of 0.8 inch H_2O. The mist eliminator was washed intermittently with only fresh makeup water--0.7 gal/min or 336 gal/shift. Two-thirds of this water was used to wash the bottom section with only fresh makeup water. The bottom was washed with 11.7 gpm at a pressure of 20 psi for 0.4

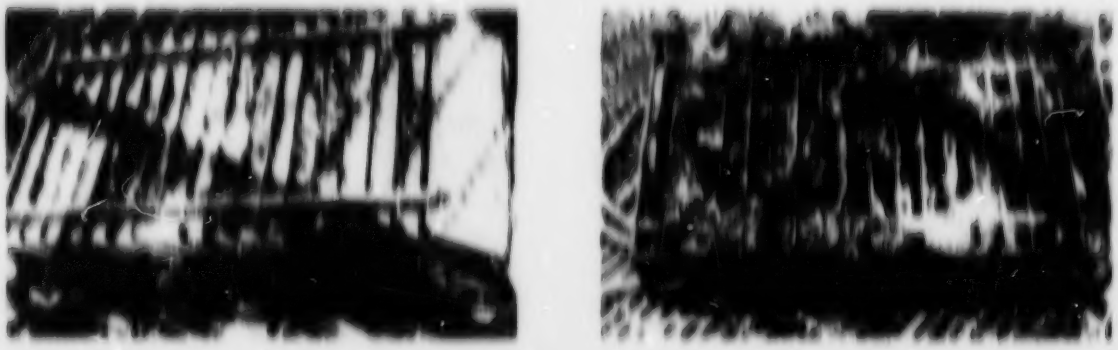

Figure 2. Top and bottom views of mist eliminator after 202 hours of operation (test ME-10).

minutes every hour. The top was washed with 8 gpm at a pressure of 10 psi for 3.5 minutes every two hours. The pressure drop gradually increased and leveled off several times before the run was terminated at a pressure drop of 1.5 inches H_2O. The run lasted approximately 300 hours. During this run, the top two passes remained clean indicating a sufficient, if not excessive, top wash. The bottom pass was plugged with soft, mud-like deposits mainly on the lower lip of the mist eliminator. Figure 2 shows the accumulation of this material on the mist eliminator. It was decided that a pressure drop of 1.5 inches H_2O was excessive as a termination point--no stopping point had been determined up to this time. A more realistic termination point of 0.5-inch H_2O was selected for the next run.

Run ME-11 began on August 6, 1975, with an initial pressure drop of 0.1-inch H_2O. Since the top passes remained clean during the previous run, half of the makeup water used to wash these passes was added to the bottom wash whose frequency was also increased. The bottom wash became 11.7 gpm at a pressure of 20 psi for 1.5 minutes every half hour. The top wash became 8.2 gpm at a pressure of 10 psi for 1.6 minutes every two hours. The pressure drop rose slowly until reaching the

Figure 3. Top and bottom views of mist eliminator after 120 hours of operation (test ME-11).

termination point of 0.5 inch H_2O after about 120 hours. Figure 3 shows the appearance of the mist eliminator at the end of this run. Its appearance was similar to that in the previous run. The lower lip was partially plugged with soft solids, but there were indications of scale deposits in this mud. The scale formation was probably due to the remaining SO_2 in the flue gas reacting with soft solids already attached to the mist eliminator thus forming the hard calcium sulfate salts. From experience at Colbert and Shawnee and from calculations on pressure drop versus percent pluggage of the mist eliminator, a pressure drop increase of 0.1-inch H_2O when starting at 0.1-inch H_2O gives a 30 percent pluggage. Therefore, a new termination point of 0.2-inch H_2O was chosen for all subsequent runs.

Run ME-12 began on August 10, 1975, with an initial pressure drop of 0.1-inch H_2O. Since the top two passes remained clean during the previous run and reducing more water from this wash to add to the bottom wash would be an almost insignificant addition, some of the available clarified liquor was used to supplement the bottom wash. Previous mist eliminator tests, prior to this project, had indicated

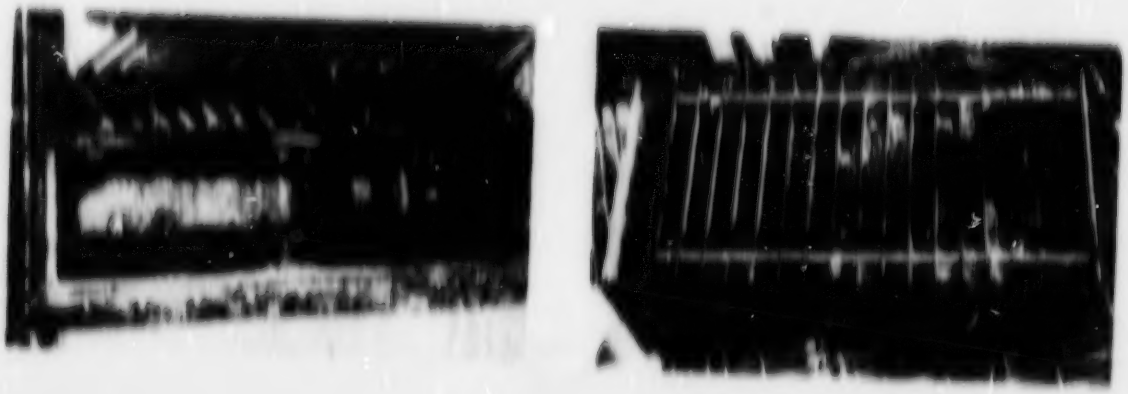

Figure 4. Side and bottom views of mist eliminator after 96 hours of operation (test ME-12).

that washing with a mixture of clarified liquor--saturated with $CaSO_4$--and fresh water would result in scale formation on the blades. With this experience, it was decided to use clarified liquor as the bottom wash and to immediately follow this wash with the fresh makeup water. Such operation reduces the possibility of any clarified liquor remaining on the blades for any length of time and becoming supersaturated with $CaSO_4$ and cause scaling to occur. The bottom wash was 11.7 gpm of clarified liquor at a pressure of 20 psi for 1.8 minutes every half hour followed immediately with 11.7 gpm of fresh water at a pressure of 20 psi for 1.33 minutes. The pressure drop during this run remained fairly constant for approximately 100 hours when the center of the lower lip began plugging thus causing termination of the run. Figure 4 shows the plugged area that caused the increase in pressure drop. The small area that had accumulated the soft deposits was believed to be caused by an uneven distribution of the wash and additional nozzles were recommended for subsequent runs.

Run ME-13 began on August 19, 1975, with an initial pressure drop of 0.1-inch H_2O. Two nozzles replaced the single bottom wash. The

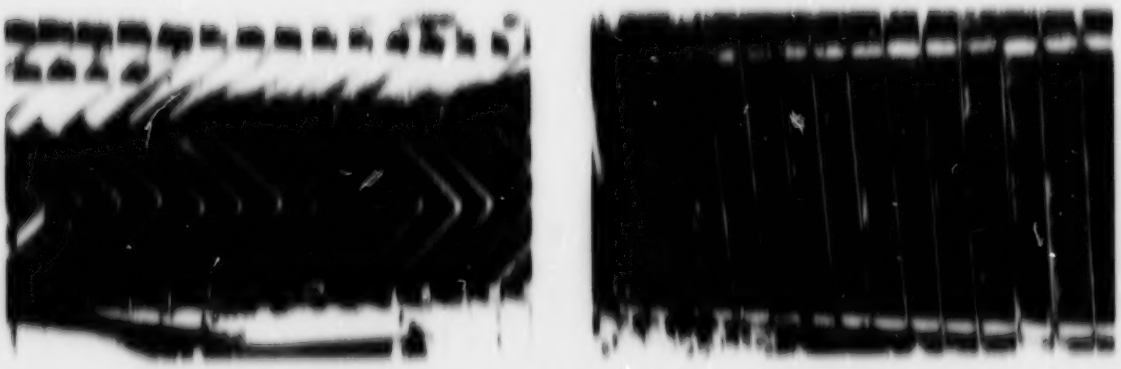

Figure 5. Side and bottom views of mist eliminator after 84 hours of operation (test ME-13).

bottom wash became 11.4 gpm of clarified liquor at a pressure of 20 psi for 1.8 minutes every half hour followed immediately with 11.4 gpm of fresh water at a pressure of 20 psi for 1.93 minutes. The top wash remained the same as the previous run. The pressure drop remained constant for approximately 100 hours when it suddenly rose to 0.4-inch H_2O. The reason for this increase is not certain. Figure 5 shows the appearance of the mist eliminator at the end of this run.

Run ME-14 began on August 23, 1975, with an initial pressure drop of 0.1-inch H_2O. It was decided to increase the clarified liquor wash to the maximum available--approximately 100 gal/shift or three times that used previously. The bottom wash thus became 11.4 gpm of clarified liquor at a pressure of 20 psi for 5.4 minutes every half hour with the fresh water wash of 11.4 gpm for 1.55 minutes at a pressure of 20 psi immediately following. There was some concern about maintaining adequate solids concentration with the addition of this clarified liquor. However, the concentrations were held fairly close to design conditions. After approximately 200 hours of operation, the run was terminated after reaching a pressure drop of 0.2-inch H_2O.

Figure 6. Top and bottom views of mist eliminator after 215 hours of operation (test ME-14).

This termination may have been premature because of the variability of the pressure drop readings. Figure 6 shows the accumulation of mud on the mist eliminator at the end of this run.

Run ME-15 began on September 1, 1975, with an initial pressure drop of 0.1-inch H_2O. The only difference between this run and the previous run is the frequency of the bottom wash was changed from every 30 minutes to every 15 minutes. The washing duration was therefore adjusted to maintain the same total wash on the bottom. The pressure drop of 0.1-inch H_2O was maintained for 1000 hours. The mist eliminator was momentarily removed after 500 hours for photographing. Figure 7 shows the appearance of the mist eliminator at that time. Figure 8 shows the appearance of the mist eliminator after completion of the long-term run.

Run ME-16 began on October 14, 1975, to test the effect of washing the mist eliminator with absorber slurry and fresh makeup water. An initial pressure drop across the mist eliminator was 0.1-inch H_2O. The bottom of the mist eliminator was washed at 15-minute intervals

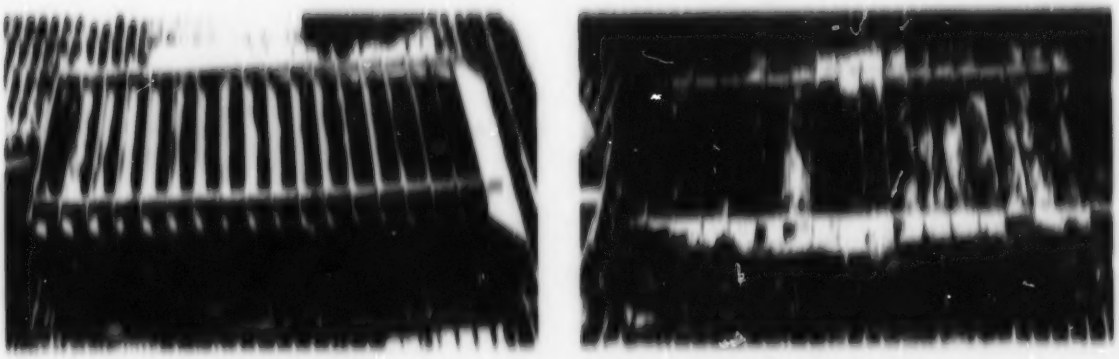

Figure 7. Top and bottom views of mist eliminator after 500 hours of operation (test ME-15).

with absorber slurry at a rate of 6 gpm for 2.7 minutes at a pressure of 15 psi with a fresh water wash of 11.4 gpm for 0.78 minutes at a pressure of 20 psi immediately following. The top wash remained unchanged. A buildup of soft mud-like solids occurred in the second pass of the mist eliminator. More than likely, this buildup was caused by an accumulation of slurry solids that were carried into the mist eliminator during the slurry wash sequence. The same header was used for the slurry wash as the makeup water wash. High-pressure air was used frequently to dislodge slurry solids from the two spray nozzles. This resulted in a portion of the solids which originally accumulated in the second pass to be blown into the third pass where they were removed by the top wash. The net effect of using high-pressure air to aid in cleaning the mist eliminator is uncertain. After 166 hours of operation, the pressure drop reached 0.8-inch H_2O and the run was terminated.

Run ME-17 began on October 21, 1979, using the same washing techniques as ME-16 with the exception that a separate spray header with larger nozzles was used for the slurry wash. These nozzles plugged with

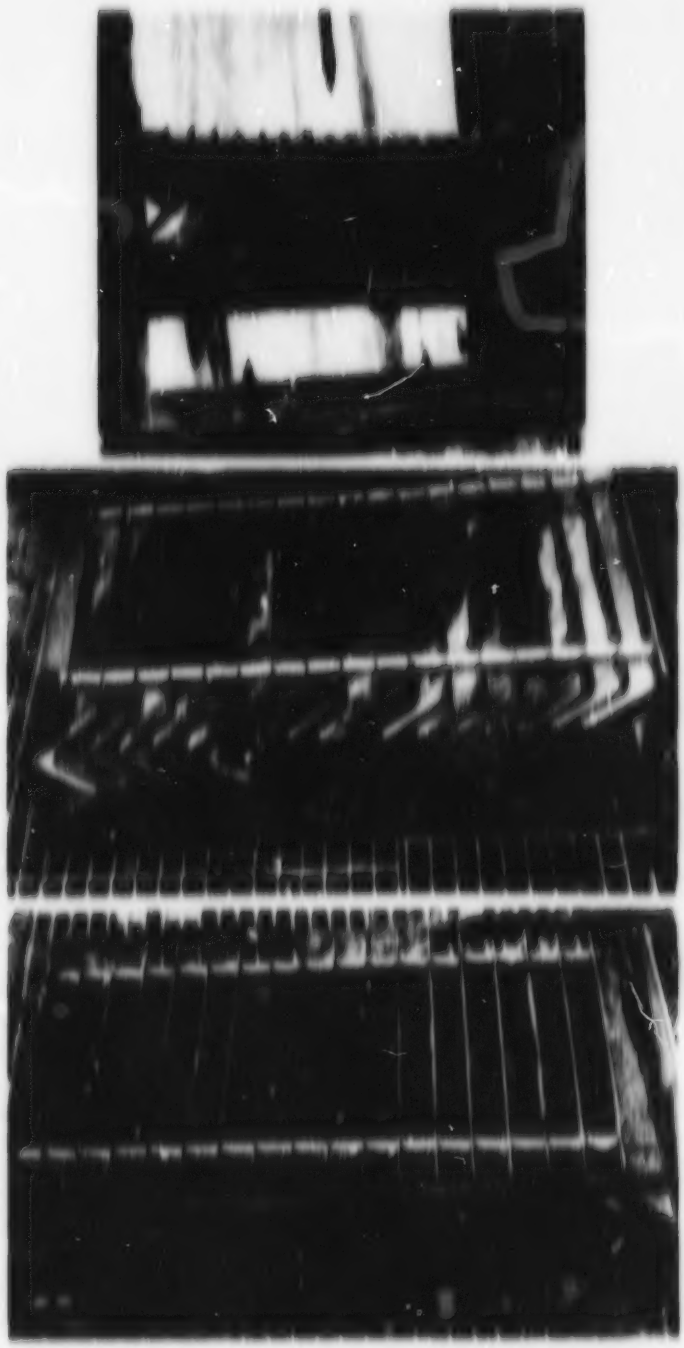

Figure 8. Side, top, and bottom views of mist eliminator after 1000 hours of operation (test ME-15).

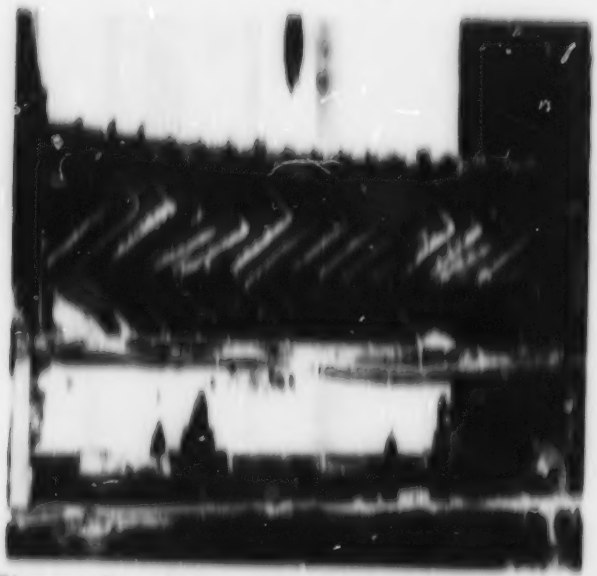

Figure 9. Side view of mist eliminator after 134 hours of operation (test ME-17).

slurry solids and high-pressure air was unsuccessful to unplug these nozzles because a sufficient back pressure could not be maintained. The solids accumulated in the second pass of the mist eliminator at a faster rate than the previous run. This may be due to the elimination of high-pressure air hitting the mist eliminator. The run was terminated after 134 hours of operation when the pressure drop reached 0.8-inch H_2O. Figure 9 shows the spray headers and the mud deposits in the second pass at the end of the run.

The absorbent in the scrubber was changed from limestone to lime. The flow diagram for the lime tests is essentially the same as the limestone tests (Figure 1). The system operated on a closed-loop basis such that the only liquor purged from the system was that contained in the discarded filter cake. This quantity of liquor amounted to about 180 pounds per hour when the filter cake contained 55 to 60 percent solids. Calcium hydroxide, manufactured by the Longview Lime Company, was used as the calcium source. Fresh calcium hydroxide slurry (30 percent suspended solids) was fed to the absorber circulation mix tank to maintain the pH of the slurry being fed to the absorber betw en 8.0

and 8.5. The amount of fresh calcium hydroxide required was equivalent to a $Ca:SO_2$ mole ratio of about 1.0. The scrubbing slurry containing 10 percent suspended solids and 1 percent dissolved solids was recirculated to the venturi and absorber at an L/G of 10 and 60 gallons per 1000 cubic feet respectively. The scrubber contained two stages (each 12 in deep) of mobile packing spheres. The Meldcraft 10-gram TPR spheres were replaced by 6-gram nitrile foam spheres manufactured by Universal Oil Products. A small mix tank was used to bring the scrubber effluent slurry into contact with the fresh calcium hydroxide slurry before it overflowed into the absorber circulation tank. The retention time of the slurry in the mix tank was about 10 seconds based on the scrubber effluent slurry rate of 144 gallons per minute. The use of the mix tank in the configuration was effective in obtaining 93 percent utilization of the calcium hydroxide. The absorber operated at a superficial gas velocity of 12.6 to 15 ft/sec. The concentration of SO_2 in the inlet flue gas varied from about 2400 to 2600 ppm. The SO_2 removal averaged 85 percent. This low removal is attributed to the height of the tower as discussed previously. The inlet and outlet dust loadings remained constant as in the limestone tests.

The chemistry of the absorption of SO_2 is different in the lime mode than in the limestone mode. This difference results in higher utilization of the absorbent and, therefore, a reduction in the amount of water removed with the sludge. The makeup water requirement for the lime mode is approximately 0.6 gal/min/MW as compared to 0.7 gal/min/MW for limestone. This reduces the quantity of water available to wash the mist eliminator.

Run ME-18 began on November 29, 1975. As a base case, the mist eliminator was washed intermittently with fresh makeup water only. The top was washed every 8 hours for 1.6 minutes at a rate of 11.4 gpm and a pressure of 10 psi. The bottom was washed every 15 minutes for 0.65 minutes at a rate of 11.4 gpm and a pressure of 20 psi. The pressure drop across the mist eliminator remained 0.1 in H_2O through 960 hours of operation. At that time, the pilot plant was shut down for the

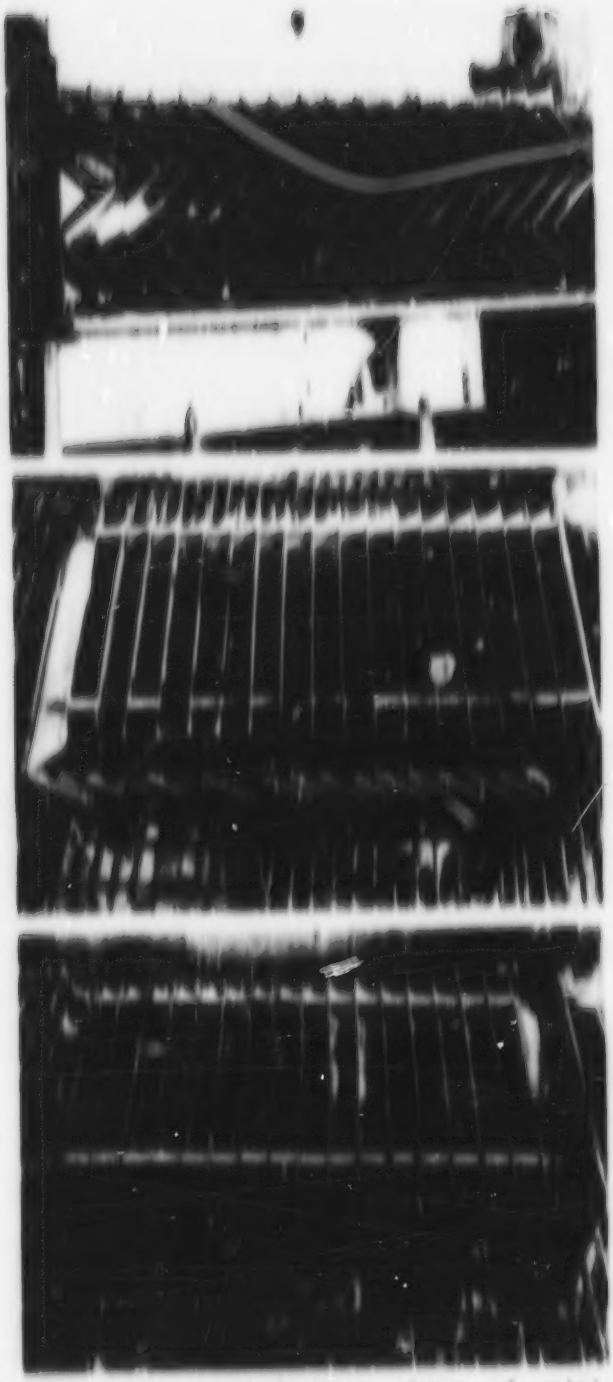

Figure 10. Side, top, and bottom views of mist eliminator after 560 hours of operation (test ME-18).

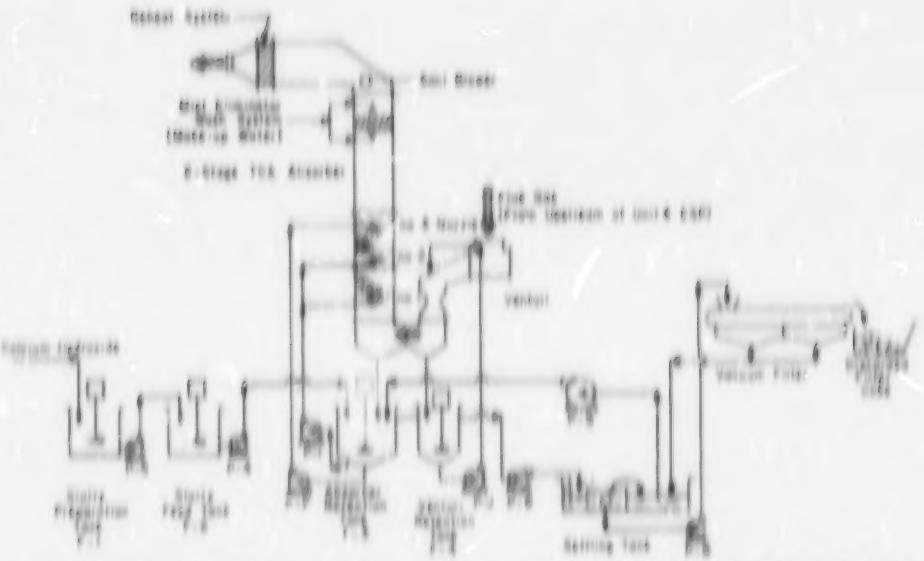

Figure 11. Modified TCA scrubber configuration for the high velocity tests.

Christmas holidays. Figure 10 shows the appearance of the mist eliminator at the end of the lime run. This run completed the mist eliminator tests in the vertical duct. Trends in operating data for all runs are graphically displayed in the Appendix.

To conduct the high velocity scrubber and mist eliminator portion of the project, the scrubber was modified to improve the gas/liquid mixing characteristics. This was done by installing a slurry inlet 10 inches below the stages that sprayed upward into each stage. The existing slurry inlet and the two additional inlets were each fitted with a low pressure nozzle (13 psi at 64 gpm). The slurry would be equally divided among the nozzles for a total L/G of 60 (L/G of 20/nozzle or 64 gpm/nozzle). The absorber contained two stages (each 9 inches deep) of 6-gram nitrile foam spheres manufactured by Universal Oil Products.

A series of air/water tests were performed to observe the drainage of the mist eliminator and the action of the TCA spheres. At 16 ft/sec, the planned operating velocity, the spheres remained fluidized, and

the drainage of water within the mist eliminator was satisfactory.

Run ME-19 began on June 16, 1976, using lime slurry and flue gas at a velocity of 16 ft/sec. The closed loop flow diagram is shown in Figure 11. The only liquor purged from the system was that contained in the filter cake. This quantity of liquor amounted to about 330 pounds per hour when the filter cake contained 55 percent solids. Fresh calcium hydroxide slurry (30 percent suspended solids) was fed to the absorber circulation mix tank to maintain the pH of the slurry being fed to the absorber between 8.0 and 8.5. The amount of fresh calcium hydroxide required was equivalent to a $Ca:SO_2$ mole ratio of about 1.0. The scrubbing slurry containing 10 percent suspended solids and 2 percent dissolved solids was recirculated to the venturi and absorber at a L/G of 10 and 60 respectively. The concentration of SO_2 in the inlet flue gas varied from about 1900 to 2700 ppm. The SO_2 removal averaged 91 percent and particulate removal 99.4 percent. Calcium hydroxide utilization was 90 percent. The pressure drop across the venturi and absorber was 6 and 5 in H_2O respectively. The mist eliminator was washed intermittently, as in ME-18, with the extra water (available from the increase in gas throughput) added to the absorber circulation tank to control the solids concentration. This washing technique permitted continuous reliable mist eliminator performance for the 500-hour long-term test. The pressure drop across the mist eliminator varied from 0.1 to 0.2 in H_2O during this test. Figure 12 shows the appearance of the mist eliminator at the end of this run.

Run ME-20 began on July 9, 1976, with limestone as the alkali source and a gas velocity of 16 ft/sec. The flow diagram for this limestone test is similar to that for the preceding test (Figure 11). The only liquor purged from this closed-loop system was that contained in the filter cake (365 lbs H_2O/hr @ 54 percent solids). Prestonia limestone (79% - 200 mesh) was fed to the system to maintain a $Ca:SO_2$ mole ratio of 1.3. The scrubbing slurry contained 10 percent suspended solids and 1.4 percent dissolved solids. The internals and slurry distribution within the absorber remained the same as in the preceding test.

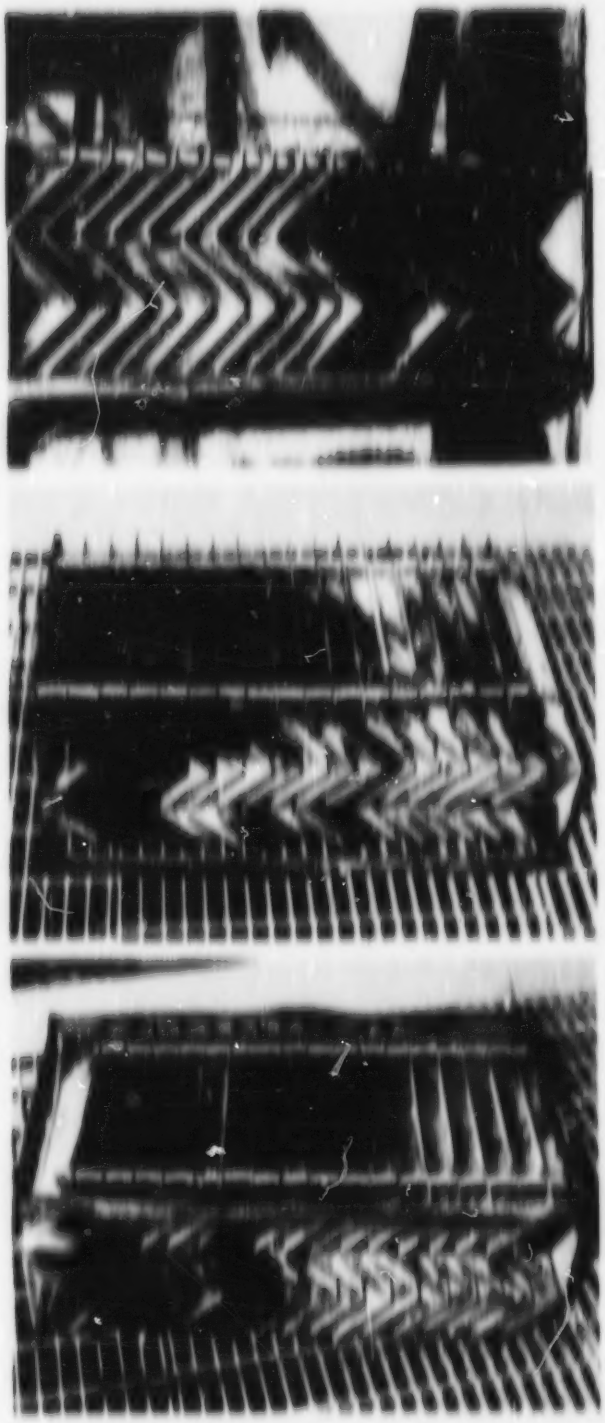

Figure 12. Side, top, and bottom views of mist eliminator after 500 hours of operation (test ME-19).

Figure 13. Top and bottom views of mist eliminator after 300 hours of operation (test ME-20).

The concentration of SO_2 in the inlet flue gas varied from 2000 to 2700 ppm. The SO_2 removal averaged 81 percent and the particulate removal averaged 99.3 percent. The mist eliminator was washed intermittently as in ME-18 and ME-19 with the extra water (available from the higher gas throughput) being used to control the solids concentration in the absorber circulation tank. During the 300 operating hours in this test, the pressure drop across the mist eliminator varied between 0.1 and 0.2 in H_2O. At the end of this test, the first pass of the mist eliminator had a light accumulation of soft mud-like solids. Figure 13 shows the appearance of the mist eliminator at this time.

On August 27, 1976, run ME-21 began. In this test, the effect of all of the slurry being introduced from the top spray (fitted with two nozzles) was studied. A stoichiometry of 1.3 was maintained with 12 percent suspended solids and 0.9 percent dissolved solids in the scrubbing system. The concentration of SO_2 in the inlet flue gas varied between 2400 and 2800 ppm. The SO_2 removal averaged 76 percent and particulate removal averaged 99.6 percent. The mist eliminator was washed intermittently as runs ME-19 and ME-20. The pressure drop across the mist eliminator

averaged 0.2 in H_2O for 162 hours of operation. At that time the first pass of the mist eliminator had a light accumulation of soft mud-like deposits. Side, top, and bottom views of the mist eliminator at the end of the run are shown in Figure 14.

Figure 14. Side, top, and bottom views of mist eliminator after 162 hours of operation (test ME-21).

4. DISCUSSION OF RESULTS

Previous limestone tests at the Colbert pilot plant have indicated that the mist eliminator requires continuous washing with fresh water at a rate of 1 gpm/ft^2 face area as compared to the vendor recommended wash rate of 5 gpm/ft^2. This amounts to about 3.4 gpm of fresh water. To operate the scrubbing system closed loop, the allowable makeup water amounts to 0.7 gpm. Less than one-fifth the amount specified by vendors and prior tests. In a previous TVA study[1] on entrainment separators, the mist eliminator was placed vertically in a horizontal duct and the wash water was recycled to maintain closed-loop operation. This method resulted in hard gypsum scale formation on the mist eliminator blades. The addition of sodium carbonate to this wash system allows the sulfate formed to remain in solution thus preventing scale formation on the blades. The separation of this wash water from the scrubbing liquor is easy in the configuration used. A mist eliminator placed horizontally in a vertical duct has been the standard practice, however, a lot of problems have plagued its reliability. Therefore, TVA with funding by EPA, undertook the task of finding a washing technique to maintain continuous reliable mist eliminator performance at the 1-MW level.

The mist eliminator in the pilot plant was repositioned between the third and fifth grids of the TCA absorber (highest point possible before leaving the tower). Observation windows were also installed to visually detect the effectiveness of the washing patterns. A perspective view of the Colbert pilot plant showing the major pieces of equipment is shown in Figure 15.

The mist eliminator tested during the project was the three-pass, 90-degree bend, chevron-type with 1½-inch spacings as shown in Figure 16.

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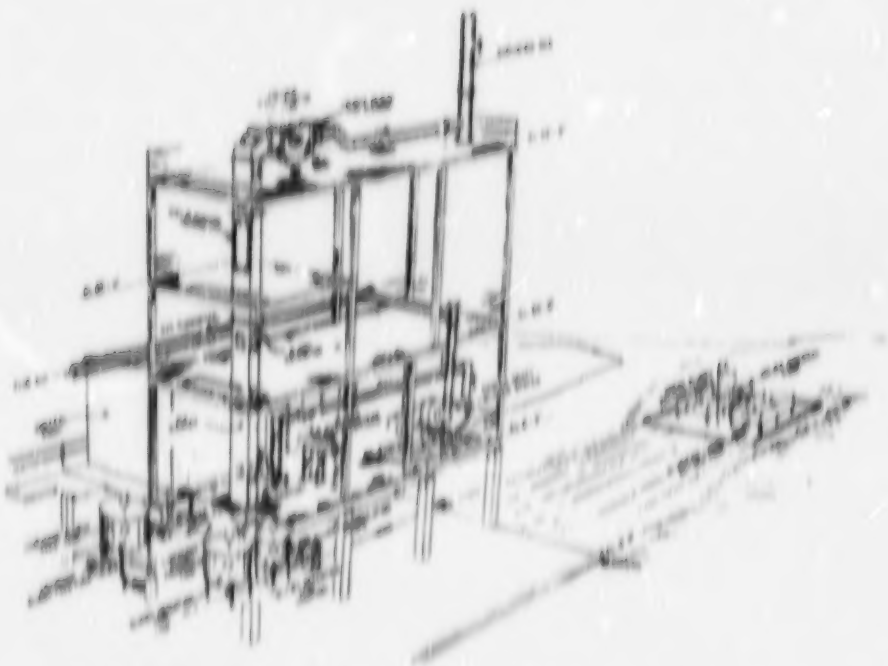

Figure 15. Perspective view of Colbert pilot plant.

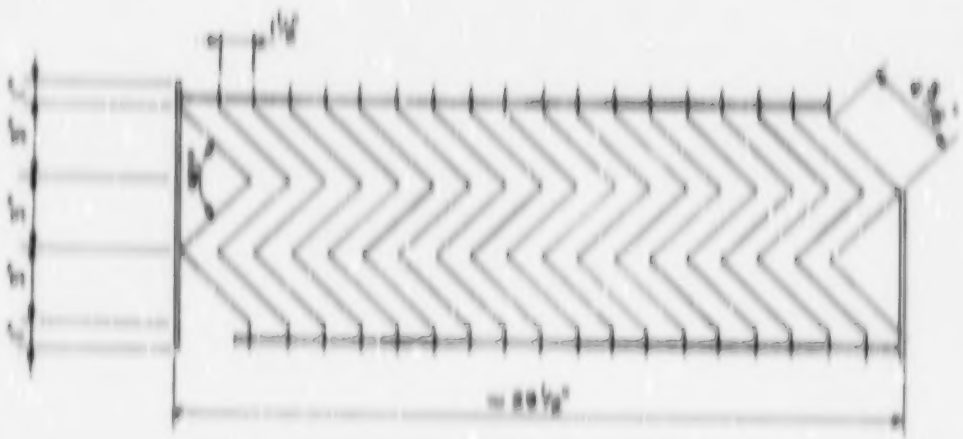

Figure 16. Chevron mist eliminator.

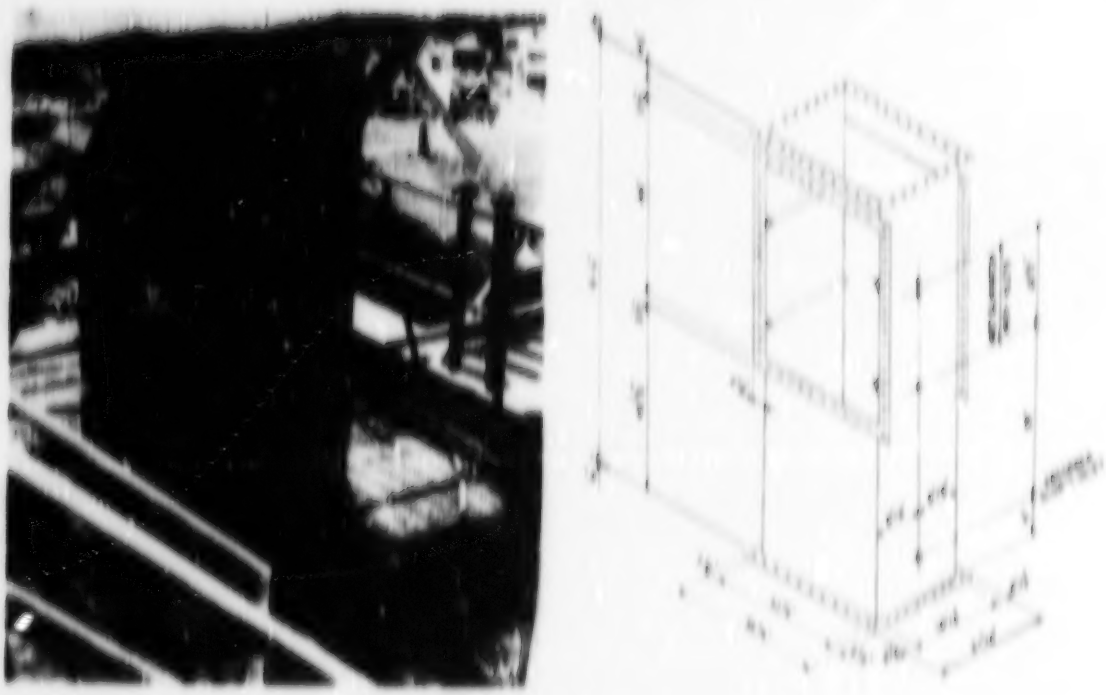

Figure 17. Mist eliminator test module.

Other mist eliminator types--Chevron with larger spacings, open vane, and Koch tray--were planned to be tested if the Chevron type could not be kept unplugged. The Chevron-type mist eliminator was placed in the horizontal position in the vertical absorber tower. Figure 17 shows a photograph of the test module and its dimensions for viewing the operation of the mist eliminator.

Air-water tests were performed to observe the drainage of the (X)^{0} bend, 3-pass, Chevron-type mist eliminator when washing from the top and/or bottom. Within the passes of the mist eliminator, the entrained water, bottom wash water, and water from the top wash spray drained satisfactorily at gas velocities up to 16 ft/sec (larger spacings of Chevron type were not as effective in mist removal).

During the top wash sequence, water entrainment from the mist eliminator amounted to over 25 percent by weight of the gas entering the reheater. This water content is unacceptable for reheat requirements if continuous washing from the top is used. However, intermittent washing was planned, and the average water entrainment, 0.2 to 0.3 percent by weight, is acceptable for efficient reheat performance. The water grain loading leaving the Chevron mist eliminator is shown in Table 1.

Previous testing of limestone scrubbing at Colbert has shown that continuous washing with fresh makeup water only was insufficient to keep the mist eliminator clean. Blending of the fresh makeup water and clarified liquor was found to be disasterous because additional SO_2 was absorbed by this liquor and hard gypsum scale formed on the mist eliminator blades. Tests at TVA's 10-MW Shawnee test facility did not observe scale formation or excessive solids deposition when using a clarified liquor/makeup water wash,[2] however, this TCA scrubber had a gas velocity of 8.6 ft/sec with a much lower gas velocity through the mist eliminator whereas the Colbert pilot plant had a gas velocity through the mist eliminator in excess of 12.6 ft/sec. Testing by organizations outside of TVA found an improvement to cleaning the mist eliminator with high pressure sprays and copious amounts of water. Based on the above information, a test program was set up to wash the mist eliminator intermittently from the top and bottom with fresh water--as a base case. Over 90 percent of this water was used for the hourly bottom wash and the remainder for the top wash every two hours. The pressure drop across the spray nozzles was 80 and 10 psi respectively. As expected, the bottom pass of the mist eliminator plugged with soft mud-like solids rapidly while the top remained clean. Cutting the top wash in half and adding this water to the bottom and increasing the washing frequency did not help. Since more water was needed for the bottom wash, a portion of clarified liquor was used. The clarified liquor wash was followed immediately by the fresh water wash. In this manner, the fresh water washed the clarified liquor off the blades before scale formation could occur. Increasing

TABLE I. PERFORMANCE OF THE THREE .625, 90° BEND CHEVRON MIST ELIMINATOR DURING AIR/WATER TESTS

Superficial Velocity ft/sec	Washing Rates gal/min Bottom	Top	Exit Gas Loading Grains Water Per Cubic Foot
5	a	a	.007
7.5	a	a	.006
10	a	a	.008
12.6	a	a	.001
16	a	a	.001
5	3.3[c]	a	.007
7.5	3.3	a	.010
10	3.3	a	.008
12.6	3.3	a	.003
16	3.3	a	.02
5	8[d]	a	.007
7.5	8	a	.006
10	8	a	.008
12.6	8	a	.006
16	8	a	.01
5	a	3.3[c]	b
7.5	a	3.3	b
10	a	3.3	b
12.6	a	3.3	b
16	a	3.3	b
5	a	4[c]	b
7.5	a	4	b
10	a	4	b
12.6	a	4	b
16	a	4	b

a Mist eliminator not washed.
b Entrainment too heavy to measure.
c Bete TF1/4 FC nozzles with pressure drop of 8 and 10 psi at 3.3 and 4 gal/min respectively.
d Bete TF3/8 FC nozzle with pressure drop of 10 psi at 8 gal/min.

Note: A constant L/G of 50 was maintained in the scrubber for each gas velocity.

the clarified liquor wash to the maximum available and increasing the frequency to every fifteen minutes for the bottom wash, keeping the top wash the same, was found to be very effective. A 1000 hour long-term run was accomplished while maintaining a constant pressure drop across the mist eliminator element. At this time, the mist eliminator had only minor deposits of mud-like deposits on areas missed by the wash sprays. A summary of the test conditions and other information leading to this test is shown in Table 8. More detail of these tests is provided in the previous section.

Tests were also conducted to observe the effect of washing the bottom of the mist eliminator with limestone slurry followed by fresh water wash. Soft mud-like solids accumulated in the second pass of the mist eliminator because the pressure of the sprays forced the limestone slurry into this pass and the fresh water wash, from a separate header, could not effectively reach this area. During these tests, high pressure air was used to clean the slurry wash spray nozzles. This air apparently dislodged part of the solids accumulated in the second pass and these could therefore be washed away by the top wash. The use of high pressure air may be an aid in cleaning the mist eliminator, but its use needs to be explored in more detail than the preliminary observations made here.

When the alkali source was changed from limestone to lime, the washing technique of intermittent fresh makeup water was again used as a base case. This washing technique was sufficient to maintain a constant pressure drop across the mist eliminator element for a 960-hour long-term run. Visual inspection of the mist eliminator during this run revealed no accumulation of solids occurring. The lower wash water requirement is believed to result from the lime mode operating at unit stoichiometry rather than a 1.5 stoichiometry in the limestone mode. This lower stoichiometry apparently reduces the amount of unreacted alkali being entrained into the mist eliminator where it can accumulate and/or react with residual SO_2 to form hard scale.

[illegible]

The above mist eliminator tests have indicated that proper implementation of the available wash water and wash frequency is the key contributor in maintaining continuous mist eliminator performance. These results do not say that all mist eliminator problems are solved, but the progress in that direction is certainly encouraging.

The last phase of the project was designed to test the mist eliminator in an advanced high velocity scrubber. The TCA scrubber was modified with the addition of a slurry spray below each of the two beds of TCA spheres spraying cocurrent to the gas flow. The scrubber liquor was equally distributed between these two inlets and the previous slurry inlet above the top bed (also installed with a low pressure nozzle). The same mist eliminator and positioning were used.

Air/water tests were done to observe the drainage of water from the mist eliminator and action of the TCA spheres. At 16 ft/sec, the mist eliminator drained properly. The TCA spheres remained mobile even at this high gas velocity.

A comparison of the TCA lime scrubbing data at 12.6 and 16 ft/sec is shown in Table 3. The SO_2 removal at the higher gas velocity was better--around 91 percent versus about 85 percent at the lower gas velocity. This higher SO_2 removal is believed to be attributed to improved mixing characteristics resulting from the higher gas velocity and the effect of the modification of the slurry sprays. Previous work at the Shawnee test facility also indicates that increasing the gas velocity improves the mixing characteristics of the gas and slurry thus improving SO_2 removal. The better mixing apparently allows more dissolution of the lime and, with the basic material being replenished more rapidly, improvement of SO_2 removal. The same effect is believed to have occurred here at Colbert. Modifications made to the scrubber are also believed to improve the SO_2 removal efficiency. The new inlets spray the slurry cocurrently with the gas into the beds of spheres where the retention time of the slurry is apparently increased by the force of the gas and sprays. In addition, the inlets were fitted with lower pressure spray nozzles which produce smaller droplets than the previous

TABLE 3. COMPARISON OF TCA LIME SCRUBBING DATA

GAS VELOCITY (ft/sec)	12.5	16
L/G (gal/1000 ft^3)		
Venturi	10	10
Absorber	60[a]	60[b]
STOICHIOMETRY ($CaHSO_3$ mole ratio)	1.0	1.0
SOLIDS (% by wt.)		
Suspended	10	10
Dissolved	1	2
pH	8.9	8.9
PRESSURE DROP (in H_2O)		
Venturi	5	6
Absorber	7	9
SLURRY NOZZLE PRESSURE (psi)	9[c]	13
PARTICULATE REMOVAL (%)	99.5	99.4
SO_2 REMOVAL (%)	80	91

a all at top

b L/G = 20 below first bed
L/G = 20 below second bed
L/G = 20 top

c open pipe distributor

open pipe distributor. The smaller drops provide more surface area available for contacting the SO_2 in the gas.

A series of short tests were conducted to determine the SO_2 removal efficiencies of the sprays in the modified configuration. The results of these tests are shown in Table 4. The venturi removes 24 percent of the incoming 2040 ppm SO_2; hence, approximately 1550 ppm SO_2 enters the main absorber vessel. With only the bottom absorber spray operating, 38 percent of the 1550 ppm SO_2 was removed leaving 959 ppm SO_2. The second spray removed 49 percent of the remaining SO_2 to leave 490 ppm in the gas. With the third spray in service, 54 percent of the 490 ppm was absorbed by this spray. The sprays obtain the liquor from the same source so the dissolved basic material is virtually the same in all sprays. Hence, as a portion of the SO_2 is removed in each stage, the ratio of basic material in the next stage to the SO_2 remaining in the gas increases. Therefore, the effective stoichiometry in the liquid phase is higher. Another less dominant but important consideration that may influence the increase in SO_2 removal per stage is a higher residence time of the slurry which is believed to result from one or more of the following: (1) the bottom two nozzles spray the slurry the same direction as the gas flow thus the absorber acts like a cocurrent scrubber for about two-thirds of the scrubbing section, (2) the slurry from the second spray has an additional four feet to react with the SO_2 than the slurry from the bottom spray, and (3) interaction of the sprays occurs, e.g., bottom spray keeps the liquor from the second spray in the bed for an additional length of time. The top spray proved to be beneficial not only from an SO_2 removal viewpoint but also as a mechanism that assisted mist eliminator performance. Apparently, the downward spray promoted the coalescing of the slurry droplets thus reducing the entrainment. In addition, the force of the top spray helped prevent the TCA spheres from becoming impinged upon the top retaining grid.

The mist eliminator was kept clean for a 500-hour long-term run with lime by the same washing technique as the previous successful lime run. Since the scrubber operated at a higher gas throughput, there would be

more makeup water available for washing the mist eliminator. This extra water was not required for the mist eliminator wash and was used to help control the solids content of the clarified liquor. The higher gas throughput increased the liquor flow through the settling tanks thus decreasing the residence time of the slurry in these tanks--designed for a 1-MW scrubber. Prior to the start of these tests, it was believed a problem of solids content control of the clarified liquor would arise. However, with proper implementation of water, the solids content was controlled satisfactorily. For larger scale scrubbers of this type, the size of the thickener or settling areas need to be in proportion to the operating conditions expected.

A comparison of the limestone scrubbing data at 13.6 and 16 ft/sec is shown in Table 5. The SO_2 removal efficiency was higher at 16 ft/sec than that observed in the previous limestone runs at lower gas velocities--91 percent versus 73 percent. This higher SO_2 removal is attributed to the improvement of the gas/liquid mixing characteristics as discussed previously. In addition, the L/G ratio for the high velocity tests was increased from 50 to 60 gal/1000 ft^3 gas. A higher L/G generally increases SO_2 removal. When all of the scrubbing liquor was sprayed on top of the bed, the SO_2 removal efficiency decreased to 76 percent. An explanation of this phenomenon may be the nozzles spraying the slurry onto the bottom of the beds provide gas/liquid mixing characteristics unobtainable from the top slurry spray alone.

During the high velocity limestone tests, the stoichiometry was reduced from 1.5 to 1.3 to increase limestone utilization and reduce the amount of unreacted material being carried into the mist eliminator thereby reducing plugging problems. This reduction in stoichiometry increased utilization from about 49 to 60 percent. Along with the higher utilization was an increase in SO_2 removal efficiency. The reasons for the increase in SO_2 removal was discussed previously but it is interesting that this occurred with a lower amount of limestone fed to the system. Improvement of the mixing characteristics and the dissolution of limestone presumably more than compensated for the reduction in stoichiometry.

TABLE 5. COMPARISON OF TVA LIMESTONE SCRUBBING DATA

GAS VELOCITY (ft/sec)	18.6	16	16
L/G (gal/1000 ft^3)			
Venturi	10	10[a]	13
Absorber	50[a]	60[a]	60[b]
STOICHIOMETRY ($CaCO_3$ mole ratio)	1.5	1.05	1.3
SOLIDS (% by wt.)			
Suspended	15	12	10
Dissolved	1.3	0.9	1.4
PRESSURE DROP (in H_2O)			
Venturi	9	7	7
Absorber	7	6	7
SLURRY NOZZLE PRESSURE (psi)	5[c]	15	13
PARTICULATE REMOVAL (%)	99.4	99.6	99.3
SO_2 REMOVAL (%)	73	76	81

a all at top

b L/G = 20 below first bed
L/G = 20 below second bed
L/G = 20 top

c open pipe distributor

The lower stoichiometry apparently helped the performance of the mist eliminator which was washed intermittently with fresh makeup water only. After 300 hours of operation, the first pass of the mist eliminator had a light accumulation of soft mud-like solids. This buildup was much lower than that experienced before when only fresh makeup water was used for washing. Therefore, a reduction in the amount of available, unreacted material being blown into the mist eliminator should reduce the probability of pluggage--as indicated by the results of this test. This result is similar to tests conducted at Shawnee.[3]

The particulate removal for the high velocity tests averaged 99.3 percent as compared to 99.5 percent removal for the lower velocity tests.

5. EXPENDITURES

A comparison of planned and actual expenditures is graphically displayed in Figure 18. The total monies allotted to this project was $600,000. This amount was necessary to complete the project.

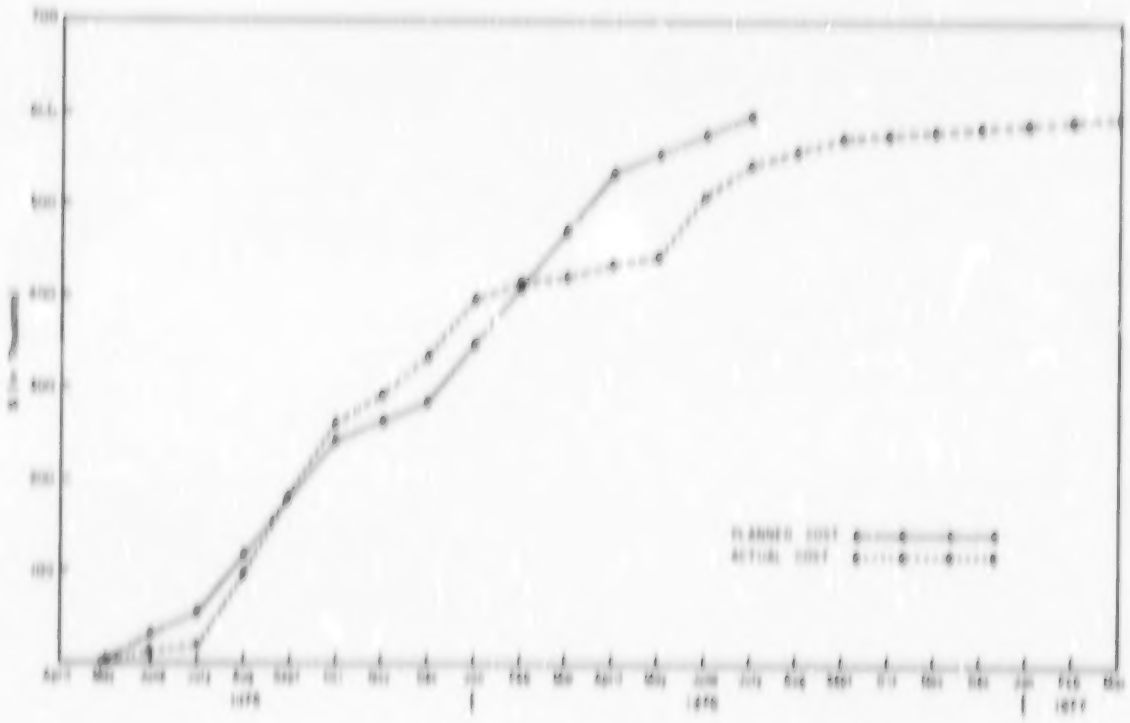

Figure 18. Comparison of planned and actual expenditures.

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2. Epstein, M. EPA Alkali Scrubbing Test Facility: Advanced Program-- First Progress Report, EPA-600/2-75-050, U.S. Environmental Protection Agency, Washington, DC, September 1975, 170 pp.

3. Head, H. N. EPA Alkali Scrubbing Test Facility: Advanced Program-- Second Progress Report, EPA-600/7-76-008, U.S. Environmental Protection Agency, Washington, DC, September 1976, 377 pp.

CONVERSION FACTORS

The Environmental Protection Agency policy is to express all measurements in metric units. Implementing this practice will result in undue lack of clarity. The following conversion factors are provided to convert the nonmetric units to the International System of Units (SI).

To Convert From	To	Multiply By
Inches H_2O	Millimeter Mercury (mm Hg)	1.868×10^{0}
Pound/inch^2 (psi)	Atmosphere (atm)	6.805×10^{-2}
Pound (lb)	Kilogram (kg)	4.536×10^{-1}
Gallon/minute (gpm)	Liter/minute (l/min)	3.785×10^{0}
Gallon (gal)	Liter (l)	3.785×10^{0}
Foot/second (ft/sec)	Meter/second (m/sec)	3.048×10^{-1}
Foot^2 (ft^2)	Meter^2 (m^2)	9.290×10^{-2}
Foot^3 (ft^3)	Meter^3 (m^3)	2.832×10^{-2}
Degree Fahrenheit (^{o}F)	Degree Centigrade (^{o}C)	$t_C = (t_F - 32)/1.8$

APPENDIX

TRENDS IN OPERATING DATA

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